PHYSICS RESEARCH AND TECHNOLOGY

ADVANCES IN RADIOMETRY RESEARCH

PERRY XIAO, PHD

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Chapter 1

RADIOMETRY IN A NUTSHELL

I can't change the direction of the wind, but I can adjust my sails to always reach my destination.

- Jimmy Dean

1.1. WHAT IS RADIOMETRY?

Radiometry is a fascinating, fast growing area, which often involves complex mathematics, physics, electrical and electronics, mechanics and a lot of software programming. So before we dive into the nitty-gritty of radiometry, let us begin with a simple introduction, i.e. radiometry in a nutshell.

The word radiometry is made of "radio-" and "–metry." "Radio-" means radiation, and "–metry" means measurement. Therefore, radiometry is all about measuring the radiation, and more specifically, measuring the electromagnetic radiation. Electromagnetic radiation is the emission of energy by electromagnetic waves, i.e., light. Light is made of photons, and each photon carries a specific amount of energy, $E = h\nu$, or $E = hc/\lambda$, where h is Planck's constant, ν is the frequency of the light. The frequency of the light can be expressed as $\nu = c/\lambda$, where $\mathbf{c}$ is the speed of light and $\boldsymbol{\lambda}$

is the wavelength of the light. The speed of light **c** is a constant, hence the frequency of the light is inversely proportional to the wavelength of the light. So for photons, the higher the frequency they are, the higher the energy they have, and vice versa. Therefore the photons of blue light (higher frequency, shorter wavelength) carry more energy than the photons of red light (lower frequency, longer wavelength). In practice, radiometry is often referred to the measurements of infrared, visible, and ultraviolet light. Radiometry is different from photometry, which is the science of dealing with how electromagnetic radiation is perceived by the human's eye.

All the objects with a temperature above absolute zero kelvin (−273°C) emit electromagnetic radiation, at almost all the wavelengths, due to the random motions of molecules, atoms and particles. The total amount of energy emitted by the object is dependent on the object's temperature. The energy emitted at different wavelength is different, and there is one wavelength that has the maximum intensity. As the object is getting hotter, the total amount of emitted energy increases, and the wavelength that has the maximum intensity shifts toward shorter wavelengths. This is why the blue color flame has higher temperature of the red color flame.

Radiometry can be divided into passive radiometry and active radiometry. Passive radiometry means measuring the electromagnetic radiation passively, without an external light source. Active radiometry means measuring the electromagnetic radiation changes due to an external light source. By measuring the radiation from a sample, we can understand the properties of the sample, such as temperature, optical properties, thermal properties and its structure.

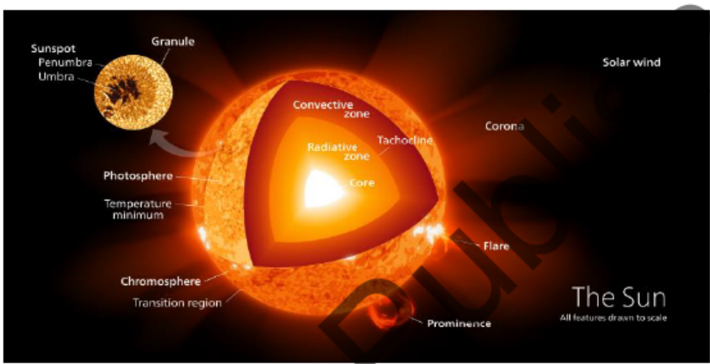
Radiometry measurements can be described by quantities such as, Radiant Energy - the energy carried by electromagnetic radiation; Radiant Power (or flux) - the radiation energy transmitted per unit time; Radiant Energy Density - the radiation energy per unit volume; Radiant Intensity - the radiation energy from a point source per solid angle, per unit time; Irradiance (incident) - the radiation energy incident upon a unit surface area, per unit time; Radiant Exitance (exiting) - the radiation energy from a unit surface area, per unit time; Radiance - the radiation energy from a projected unit surface area, per solid angle, per unit time.

1.2. Radiometry Applications

Probably the most important application of radiometry is in astronomy, to observe and study the stars. This is passive radiometry. From the light emitted by the stars we can estimate temperature of stars and what they are made of. Take the Sun for example, see Figure 1.1, from its radiation power, we can work out the temperature of the Sun, which is about 6000 degrees Celsius at the surface and 10 million degrees Celsius at its core! If we send the Sun light through a prism, we can break the light into a rainbow of colors, see Figure 1.2 (top). Because different elements in the Sun absorbs different colors of light, by examining which colors are missing, e.g., the dark bands, we can figure out what elements present on the Sun that absorb the colors and caused dark bands. The Sun is roughly made of three quarters of hydrogen and one quarter of helium.

We can also study the stars' movements. According to the Doppler effect, when a star is moving towards us, the light it emits will increase its frequency, or reduce its wavelength, this is called blue shift. When a star is moving away from us, the light it emits will reduce its frequency, or increase its wavelength, this called red shift, also see Figure 1.2 (bottom). Because the observations show red shift in almost all the stars, we can conclude that all the stars are moving away from us. This means the universe is expanding. If we reverse this process, then all the stars much have come from the same place initially. This is where the Big Bang theory (not the American television sitcom!) comes from. According to the Big Bang theory, the universe started from a gigantic, enormous explosion from a singular point. This is when the universe started, this is also when the time started. Nobody knows what happened before the singular point.

From the Doppler effect, we can also work out the speed of the stars. The observations show that the speed of a star can be expressed as, $V = H_0 D$, where H_0 is Hubble constant, and D is the distance of the star, this called Hubble's Law. The latest value for H_0 is 72.5 (km/s) per megaparsec. Parsec is a unit in astronomy to measure the distance of stars. One parsec is 3.3 light-years. One megaparsec (Mpc) is a million parsecs, which is about 3.09×10^{19} km. From Hubble's Law, we can estimate the time for the star to reach its current position, $t = D/V = 1/H_0$, this is largely treated as the age of the university, which is about 13.77 billion years. Figure 1.3 shows the timeline of the universe expansion.



Source: https://en.wikipedia.org/wiki/Sun.

Figure 1.1. The structure of the Sun.

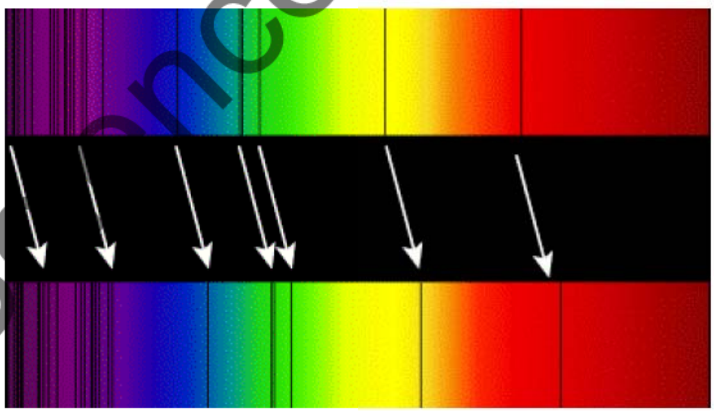
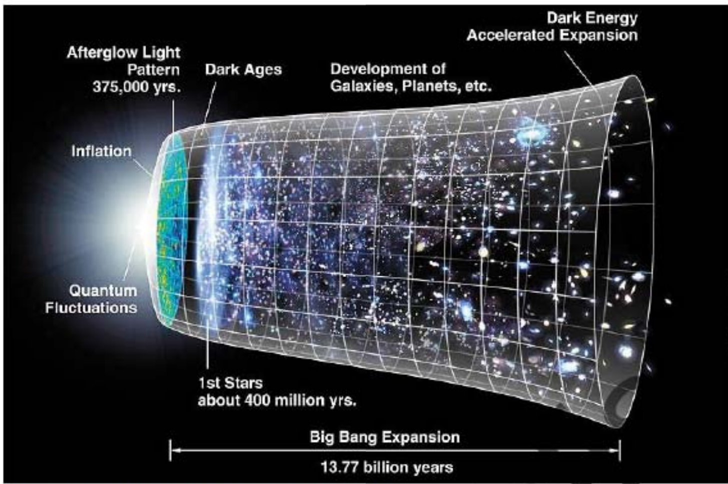


Figure 1.2. An example of a ray of light from the Sun (top) and a ray of light from a far off galaxy (bottom). All the lines shift towards the red end of the spectrum due to red shift. (Modified from Source: https://simple.wikipedia.org/wiki/Red_shift).



Source: https://en.wikipedia.org/wiki/Big_Bang.

Figure 1.3. The timeline of the metric expansion of the universe.

The observations also show that the stars are moving away faster and faster from us. The universe is expanding at an accelerating speed! The Big Bang theory could not explain this, so the scientists suggested there must be a dark energy exist that caused this acceleration. It is called dark energy because we know it does exist but we can neither measure it nor observe it.

Another interesting thing is the dark matter, which we could not see or measure it either. But many compelling evidences, such as galaxy rotation curves, galaxy velocity dispersions, galaxy clusters and gravitational lensing, predict the existence of the dark matter. According to general relativity theory, when a light is passing through a massive star, the gravitation force will cause the light to bend like a lens, this is called gravitational lensing. From gravitational lensing analysis we can predict the existence of dark matter and the amount of the dark matter. It is estimated that dark energy makes 68% of the universe, and dark matter makes 27% of the universe. So dark energy and dark matter combined together makes 95% of the universe! I found this fascinating, after all the brightest scientists such Isaac Newton, Albert Einstein, and Steven Hawkins etc., we have only managed to understand 5% of the universe. If you are interested to read more about the universe, or cosmology, there are two excellent easy-to-read books from Steven Hawkins, "A Brief History of Time" and "The Universe in a Nutshell."

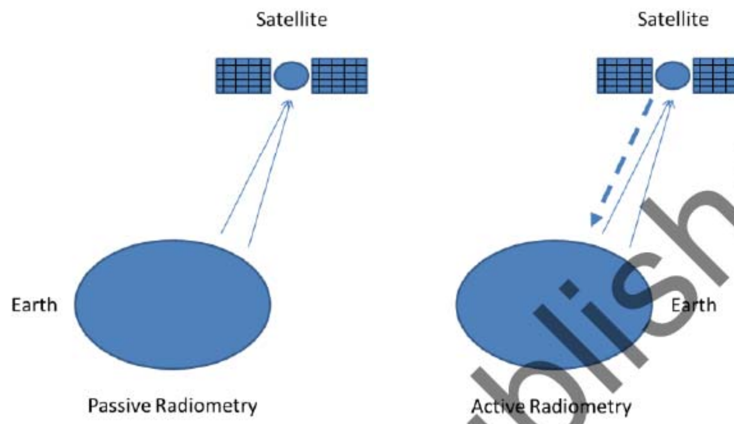
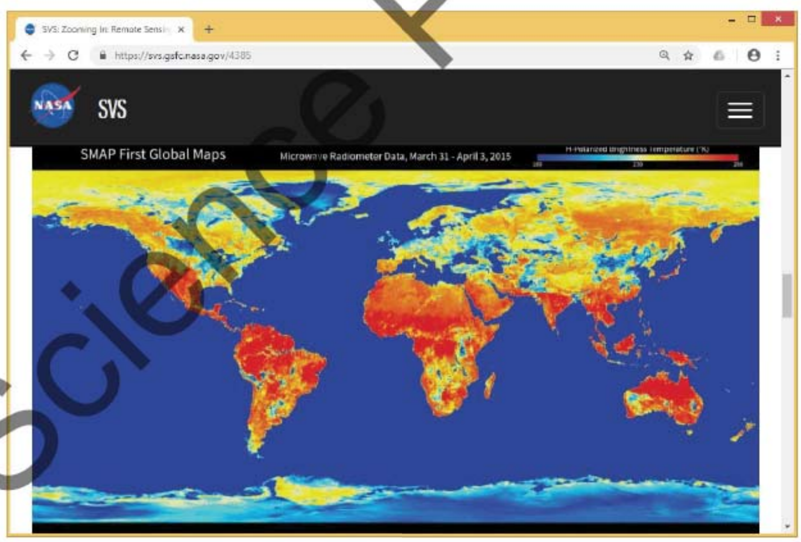


Figure 1.4. Illustration of passive remote Sensing (left) and active remote sensing (right).



Source: https://svs.gsfc.nasa.gov/4385.

Figure 1.5. The NASA's Soil Moisture Active Passive (SMAP) map of global soil moisture and freeze/thaw state.

Radiometry has also been extensively using in the Earth remote sensing. This can be both passive radiometry and active radiometry, as illustrated in Figure 1.4. For passive radiometry, it just collects the radiation from the Earth passively, whilst for active radiometry, it emits light to the Earth, normally microwave, then measure the radiation reflected or backscattered from the Earth. Earth remote sensing can be done by using airplanes, satellites or drones. For example, from satellite images of the Earth, we can study the weather, the chemicals in the atmosphere, deforestation, as well as glacial ices in the Arctic and the Antarctic. Figure 1.5 shows the NASA's SMAP (Soil Moisture Active Passive) satellite global map of microwave radiometer data with 30 x 30 meters spatial resolution. The SMAP mission is to produces high-resolution maps of global soil moisture, as well as freeze/thaw state.

The infrared camera, also called thermal camera, is another interesting application of the radiometry. With infrared camera, we can remotely measure the temperature of objects, such as the furnace, the equipment, and electrical circuit etc. We can also use it for monitoring the insulations of the buildings, for night vision, or for searching missing people that are possibly buried underneath the debris, following a natural disaster such as earth quake or tsunami.

To date, radiometry has been widely used in industrial, environmental, space, medical, agriculture, and defense applications. Chapter 2 has more details on radiometry, photometry and colorimetry. Chapter 3 has more details on the theoretical background of radiometry. Chapter 4, 5 and 6 have more details about the radiometry sources, detectors and optics. Chapter 7 – 9 have more details on the latest research in radiometry. Chapter 10 has more details on prototyping low cost radiometry measurement devices.

1.3. SUMMARY

This chapter provides an easy-to-read introduction to radiometry and its common applications, such as in astronomy, and in earth remote sensing. More details about radiometry and its terminology are available in the coming chapters.

1.4 QUESTIONS

Q1.1. Define the terms of electromagnetic wave, frequency, wavelength and speed of light.
Q1.2. What is Planck's constant?
Q1.3. What is the difference between astronomy and cosmology?
Q1.4. What is Doppler Effect?
Q1.5. What is red shift and blue shift?
Q1.6. What is Hubble's law?
Q1.7. What is a megaparsec?
Q1.8. What is General Relativity?
Q1.9. What is gravitational lensing?
Q1.10. What is passive radiometry and active radiometry?
Q1.11. What is NASA's Soil Moisture Active Passive (SMAP) mission?